ON CERTAIN FEATURES OF PROGRAMMING A SEQUENCE OF HUMAN ACTIONS

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Among the problems to be solved by a pilot-astronaut on board a spacecraft will certainly be those in which individual actions are executed in a definite, rigidly fixed order. The completion of such tasks can be represented by the scheme of an ordered sequence of descrete motor acts. This type of schematic representation makes it possible to investigate certain essential characteristics of the execution process, such as the order of the actions and the distribution of the individual time intervals. The obtaining of information on these characteristics may serve as one of the experimental principles for constructing block diagrams of control of series of motor acts in man, and also to work up tests permitting evaluation of certain aspects of the functioning of a human operator.

In recent years many authors have expressed the idea that human behavior should be considered from the viewpoint of programs which are synthesized in the central nervous system, specifying the actions which are necessary to solve this or that problem [1-4].

If we accept this viewpoint of program control of an ordered sequence of motor acts, we are faced with the problem of the features such a program should possess for a given concrete problem to be solved with certainty with this program.

In the preceding investigation one of us [5] demonstrated that in the process of formation of a sequence of actions by man, an inportant role is played by a mechanism which combines individual actions into blocks, consistent with the structure of the problem to be solved. This permitted us to postulate that programming a series of actions is tied in with synthesis in the human central nervous system of rules indicating the method by which the individual acts making up the sequence are chosen [6]. In other words, we assume that the control program for a sequence of actions should contain the sum of information on the problem that reflects the essential features of the problem, making it possible to /62
choose the necessary actions from the available set. One such essential feature is the selection, from the sequence, of individual parts (blocks), consisting of several actions, which are linked by a common property. Thus, in the studies we made of sequences of various key-pressing actions on a panel, a description was given of a combination of four consecutive actions which, when executed by a human being, "described" the inverted letter "N" by moving the hand from key to key, or of three actions on contiguous keys, where the hand is moved in one direction, etc. It was found that the majority of people use these features of the problem.

In the present study we posed the problem of determining to what extent the size of the blocks is a factor governing the structure of a sequence of actions. For this purpose we developed an experimental schedule in which we studied

two ordered sequences of actions which were similar insofar as the set of constituent motor acts and number of elements (length of the sequence) are concerned, but which contained blocks differing in size. By comparing the speed of execution, the error distribution, and the temporal "pattern" of completion of the two sequences by the group of test subjects, we attempted to find out to what extent the feature of the problem being studied is specific and invariant.

METHOD

The experimental arrangement consisted of two relatively small (25 x 30 cm) panels. Arranged on the test subject's panel were 8 signal lights in two rows of four each and 8 keys arranged in the same order. The experimenter's panel contained 8 keys to control the signal lights and 8 monitor lights to observe the actions of the test subject.

The test subjects were persons of both sexes, 18-35 years old, with high school and college education. Two groups of test subjects participated in the experiments. The first group was made up of test persons who were performing this type of task for the first time (12 people). The entire group was taught to perform both tasks until they could be repeated without error. The group was divided into two subgroups of six men each; the order of presentation of the tasks was different in each subgroup. The second group of test subjects (10 people) participated in experiments in which the time of completion of a sequence of actions was measured. This series of experiments was carried out 8 months after the first, and some of the test subjects (7 people) were from the members of the first group. A comparison of the speed of learning problems 1 and 2 was made on the basis of data from the two groups (22 people, 1st and 2nd groups).

The instructions were issued to the test subjects before the beginning of the experiment. These instructions stated that each signal lamp corresponded uniquely to each key on the panel and requested repetition of the order of the actions, which would be shown by the experimenter by means of the signal lights. /63

The test subject, who was located in an isolated room, was demonstrated the prescribed order by successive flashing of the respective signal lights on the panel. After each demonstration of the entire series, the test subject repeated what he remembered of the indicated order by pressing the appropriate keys on the panel. This procedure was repeated until the entire sequence was repeated by the test subject completely and error-free. The entire learning process was accomplished during one experiment. Each test subject was presented in turn (with a break of not less than three days) with the two tasks of learning a sequence of actions.

Each problem consisted of a specific series of 36 sequential key-pressing operations on the 8 keys of the panel. If the keys on the panel are numbered 1,2,3,4, the problems can be written as:
5,6,7,8

Problem No. 1 — 2 3 7 6 8 4 7 3 6 5 1 2 8 3 7 2 4 8 7 3 5 6 1 2 5 2 7 4 1 6 3 8 6 3 7 6.

Problem No. 2—726734125237837 1 6 2 7 8 4 2 1 5 3 2 1 7 4 8 6 7 8 2 3 6.

After pressing the first key in the sequence, the test subject was to move his hand and press the next key in order, then move his hand to the third key, etc. If the entire prescribed course is divided into blocks of successive actions, the problems will look as shown in Fig. 1. From the figure it is evident that the order of the actions in the problems was organized in a specific manner. In Problem No. 1 the order was organized in such a way that the entire sequence can be divided into 9 blocks of four actions. The characteristic of each block is that in executing the constituent actions the hand completes a course which, so to speak, depicts a definite geometric figure or pattern (square, zig-zag, triangle, etc.). Problem No. 2 was set up so that it was possible to break it up into 12 sections of 3 actions each.

Thus, the structure of our problems was characterized by the following features:

1) consecutive actions in each problem could be combined into blocks of 4 or 3 actions;

2) the blocks were organized according to the principle of spatial proximity of the consecutive actions or of the formation of figures;

3) all the blocks in one problem were different in configuration, but identical in size.

The essential feature distinguishing one problem from the other was the size of the blocks. On this basis, in what follows we will call Problem No. 1 "four-component" and Problem 2 "three-component."

All the responses of the test subjects, both correct and incorrect, were recorded during the experiments (in report form). In addition, in the experiments with ten test subjects we recorded the entire experiment on the tape of a loop oscillograph. Recorded were the length of the responses (duration of the key-pressing action) and the pauses between responses (the time required to move the hand to the next key) in executing the sequence of actions by the test subjects. The record was made at a tape speed of 4 mm/sec, which permitted measuring the time segments with an accuracy of up to 50 msec when examining the tapes on the photoamplifier. /64

RESULTS

Learning and Error Distribution

All repetitions of each sequence by the twelve test subjects were examined with due regard to the number of motions (key-pressing actions) in each run over the entire learning period. The result of this examination is given in Fig. 2, which shows the distribution of the number of motor acts during the learning process. From the figure it is evident that in the majority of cases the test subjects repeat parts of the sequence in segments, where the number of actions is /65

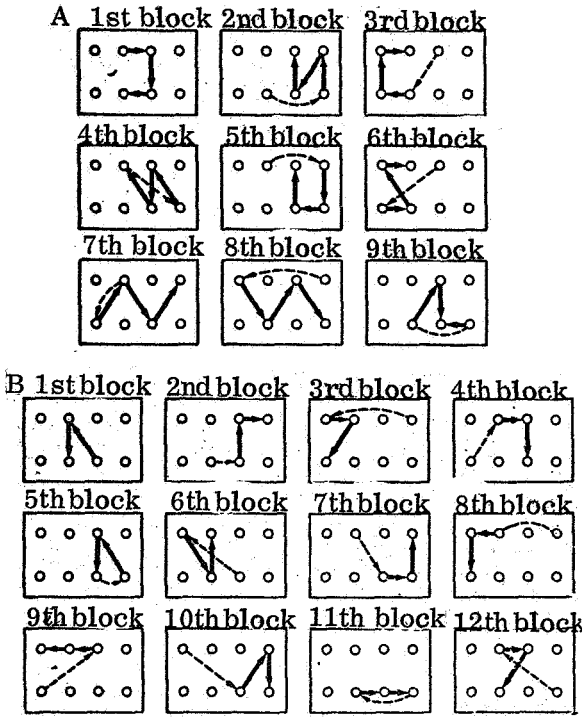

Figure 1. Schematic Illustration of a Possible Division of Problem No. 1(A) and No. 2(B) into Blocks (groups) of Actions. The Solid Arrows Indicate the Order of the Actions Within a Block; the Broken Arrows Indicate the Order of Actions when Passing from the Preceding to the Next Group of Actions.

equal to the length of the blocks making up the problem. For the four-component sequence, this was observed in 81% of all cases, and in 75% for the three-component sequence. These data allow us to assume that one of the features of the program of an ordered sequence of actions is sequential clustering into segments of different length for different problems.

Furthermore, we investigated the errors made by the test subjects at the start of training. /66 As is evident from Table 1, the number of errors in the first five trials in considerably greater than the number of correct responses. However, the majority of errors in learning the first as well as the second problem (in evaluating them in connection with the structure of the problems) are not random in nature. As a rule, responses are combined into blocks which correspond to the blocks of the given sequence. In doing so, however, we observed that either the order of actions within a block was distorted, or blocks were misplaced in the sequence, or both occurred simultaneously.

Free operation with blocks of actions is clearly evident in analyzing the order of appearance of sequences of correct responses during training. These data are given in Table 2. All possible cases of the order of priority in learning blocks of actions are divided into 3 categories:

1) learning of blocks in a sequence consistent with their position in the given series (the first block is learned first, then the second, the third, etc.);

2) inverted order of the learned blocks (the seventh, eighth blocks appear before the second, third, etc.);

3) other cases of transposition of the order of learning (the third block is /68 learned before the second, the eighth before the sixth, etc.).

The table shows that the learning of blocks in an order consistent with their location in the sequence is observed in 33% of all cases with the four-components

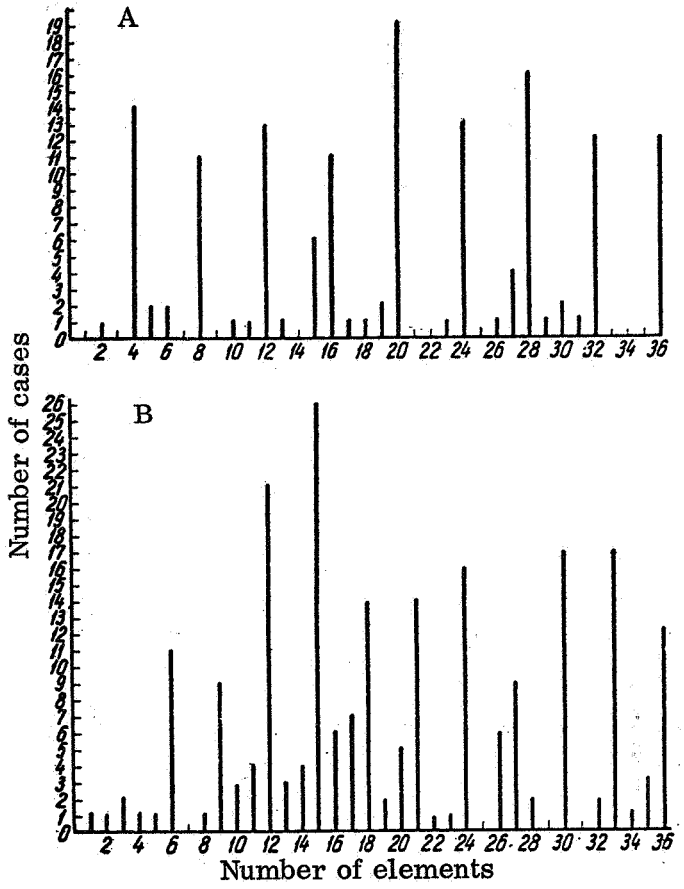

Figure 2. Distribution of the Number of Reproduced Elements in Each Run Over the Entire Learning Period of 12 Test Subjects in Problem No. 1(A) and No. 2(B).

TABLE 1. Distribution of Correct and Incorrect Responses in the First Five Sequences Reproduced

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Number of the problem	Elements repeated	Reponses						
		Correct	Erroneous					
			Total	Correct blocks mis-placed	Distorted blocks in place	Distorted blocks not in place	Incom-pleted blocks	Random errors
1	1375	464	911	288	144	200	189	90
2	1203	372	831	201	192	289	—	150

TABLE 2. Distribution of the Order of Learning Blocks of Actions

Number of the problem	Total number of cases	Distribution of the order of learning priority (in %)		
		1st category	2nd category	3rd category
1	117(100%)	33	26	41
2	168(100%)	20	37	43

problem and in 20% of the cases with the three-component one. The large number of transpositions of the order of learning entire blocks indicates that a block of responses is linked by some new unit with which the learning process is involved.

Given in Fig. 3 is an example of how one of the test subjects worked through a four-component sequence. The figure reveals that the order of sequence of the actions is distorted in a number of the blocks, in some cases the order of the correctly reproduced block is broken, some blocks are repeated, the order of priority of learning clusters does not correspond to their position in the stereotype.

On the basis of these data it can be concluded that the basic unit in learning an ordered sequence of actions is a block of actions united by a certain feature. In order to have some justification for assuming that such a block is an element in a control program, it is necessary to have proof as to the execution of the problem after it has been learned.

Time Distribution in Executing a Sequence of Actions

After the 10-man group of test subjects had learned the sequences, ten error-free reproductions from each person were recorded on the tape of the loop oscillograph. It was assumed that if a block of actions is a unit which organizes the rhythmic pattern of the entire sequence, differences between sequences of different blocks lengths should show up in the differing time patterns of the sequences.

To test this hypothesis, we measured the time intervals required to complete a single act, as considered within the framework of its position in the block and in the overall series. First, we computed the total time expended in each execution of the sequence of actions. For further analysis we chose 84 cases of completion of Problem No. 1 (9 test subjects) and 57 cases of completion of Problem No. 2 (6 test subjects). The selection principle was governed by the uniformity of the work of the test subjects; excluded were experiments in which the time difference between separate executions of the task (by the given test subject) exceeded 10 sec. We counted 588 blocks from the four-component sequence and 570 from the three-component one. The time pattern of each block was described by the following measurements:

For the four-component sequence (Problem No. 1):

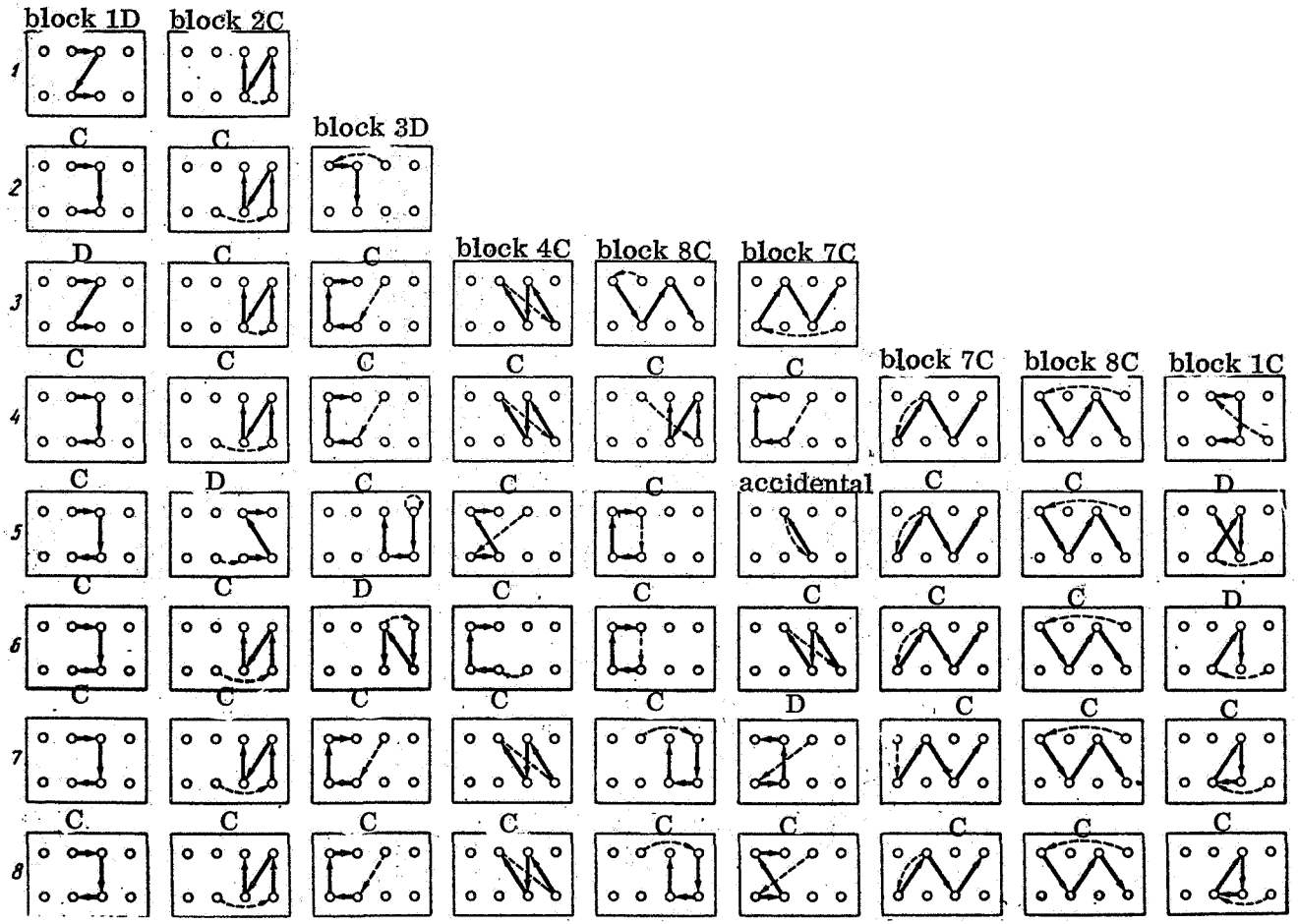

Figure 3. Reproduction by Test Subject E-v of a Sequence of Actions in Each "Step" of the Process of Learning Problem No. 1. The Figures on the Left are the Consecutive Numbers of the "Steps"; C is a Correct Block, D a Distorted Block of Actions. The Remaining Notation is As in Fig. 1.

1) the duration of the 1st motion in the block (the key-pressing time); 2) the duration of the pause between the 1st and 2nd motions; 3) the duration of the 2nd motion; 4) the pause between the 2nd and 3rd motions; 5) the duration of the 3rd motion; 6) the pause between the 3rd and 4th motions; 7) the duration of the 4th motion; 8) the pause between the 4th motion of the given block and the 1st motion of the next block (the inter-block pause). /69

The distribution of time intervals within the blocks of the three-component sequence was described in the same manner. In our computation the parameters measured for the various blocks of one problem were averaged and plotted in the form of a distribution within one "average" block. Then we calculated the mean deviations (x), the root mean square deviations (σ), and the errors of the mean (S) for each interval. The averaged data are given in Table 3.

TABLE 3. Distribution of Time Intervals in the Completion of Blocks of Actions in Problems Nos. 1 and 2

Parameters	Statistical index	Problem 1					Problem 2			
		Successive positions in the block				difference	Successive positions in the block			difference
		1	2	3	4		1	2	3	
Duration of the motions (msec)	x	460	440	490	450	30	450	410	480	
	σ	194	145	218	146		167	143	238	
	S	8	6	9	6		7	6	10	
Pauses between motions (msec)	x	580	590	600	860	260	650	610	880	230
	σ	218	170	121	655		476	238	668	
	S	9	7	5	27		20	10	28	

Remark: The semi-boldface numbers denote the values of the intervals for which a comparison was made between the significance of the differences. The corresponding values of the difference are entered in the "difference" column. In all cases the magnitude of the differences is considerable ($P < 0.01$).

As is evident from the table, the time pattern of the blocks of each problem has its own characteristic features. In the four-component blocks of Problem No. 1, the pause that corresponds to the position between blocks is considerably longer than the other pauses that separate individual motions within blocks. The same relations between intra- and inter-block pauses are observed in the blocks of Problem No. 2; here the pause separating the three-component blocks of the problem proves to be longer.

Also deserving of attention is the considerable increase in the standard rms deviations (σ) of the inter-block pauses as compared with the intra-block pauses. /70 Given in Table 4 are the frequency characteristics of the distribution for the values of the inter- and intra-block pauses in Problem No. 1.

TABLE 4. Frequency Characteristics of the Distribution of the Value of the Intra- and Inter-block Pauses in Executing Problem No. 1

Length of the pauses (msec)	Relative frequency of occurrence (%)	
	intra-block	inter-block
300—450	15	5
500—650	68	51
700—850	14	21
900—1050	1	6
1100 plus	2	17

This characteristic of the distribution of the values of the intervals we examined demonstrates that the peak of the distribution for the intra-block as well as inter-block pauses is found in a single region; the mean value of the inter-block pause increases because of the large scatter in the values of the inter-block pauses and because of the considerable number of cases in which the magnitude of these pauses is approximately double the mean value of the intra-block pauses (at a mean value of 590 msec for the intra-block pause, the number of cases in which the inter-block pause exceeds 1100 msec is 17%).

From Table 3 it is also evident that the time pattern of the problems differs also in the duration of the individual motions as a function of their location within the block. Thus, in Problem No. 1 the third motion is certainly longer than all the other motions.

Thus, the time characteristics of execution of a sequence of actions seem to favor the argument that the basic unit of a control program is a block of actions whose size is governed by the presence of a common feature that permits description of the block as a whole.

Comparative Learning Speeds

According to the literature data, the learning speed for a sequence of symbols is linearly related to the number of learned elements [7]. A similar relation was found by Bogina [6] for the case of learning a sequence of actions.

On the basis of these data we postulated that if a block of actions, and not a single motor act, is an element of the program, then the four-component sequence containing 9 blocks should be learned faster than the three-component sequence consisting of 12 blocks. /71

Given in Fig. 5 are the total data on the speed of learning of a sequence of actions. As the learning-speed criterion we took the number of demonstrations and repetitions of the sequence until the first error-free completion.

The table shows that Problem No. 1, which consists of 9 blocks of 4 actions each, is learned faster than Problem No. 2, which consists of 12 blocks (of 3

TABLE 5. Speed of Learning of a Sequence of Actions

Name of test subject	First experiment (Problem No. 1)	Second experiment (Problem No. 2)	Name of test subject	First Experiment (Problem No. 2)	Second Experiment (Problem No. 1)
1st group of test subjects			2nd group of test subjects*		
B-v...	23	25	B-va...	16	7
I-v....	25	39	E-v....	10	8
M-va..	16	20	E-v....	12	3
M-va..	10	23	Z-o....	12	7
P-va..	14	12	K-va	27	9
P-va..	14	12	L-va	19	8
P-v A..	9	11	L-va	17	10
P-vYu.	13	14	M-o	19	12
P-vYu.	9	19	M-o...	12	10
F-va...	10	15	N-v...	26	11
F-va...	6	15	R-ya..	9	6
Average speed	13.5	18.6	Average speed	16.3	8.3

actions each). The significance of these differences was evaluated by Wilcoxon's nonparametric criterion ($P<0.05$).

CONCLUSION

In formulating the problem of the present investigation, we suggested that the formation of an ordered sequence of actions is connected with the process of grouping individual motor acts, and we attempted to demonstrate that the presence of blocks (groups) and their size are factors which determine the structure of the given sequence. We examined the effect of these factors on the character of learning and executing two sequences of equal length (in number of motor acts), but different in the structure representative of the block. /72

The course of the learning process can be described by the growing number of learned acts and by the order in which they are learned relative to their position in the sequence. This characteristic can be observed in an especially convenient manner by a learning method in which the test subject himself, freely reproducing a prescribed sequence of actions, controls both the number of motions and their order of sequence.

The results of the investigation have shown that in learning each sequence the accretion and order of learning material reveals general features which are connected with the presence of the grouping process and differences which are due to the specific properties of the group (block). That the learning process has general features is manifested in the nonuniformity of accretion; rather it is stepped in nature, in that not a single motor act is added, but an entire block. The order of learning did not correspond to the order of the individual acts in

the sequence. The order of the motor acts in the block and the location of the blocks was learned separately. On the basis of these data it can be assumed that two independent processes, forming an organized sequence of learned acts, participate in learning: the process of combining single acts into blocks and the process of combining blocks. The differences in learning two sequences are due to the size of the blocks of motor acts and to the number of these blocks. In Fig. 2, which shows the distribution of the number of reproduced motor acts, it is clearly evident that the largest number of cases in Problem No. 1 relates to the reproduction of 4, 8, 12, 16, ... motor acts. In Problem No. 2 the most frequent cases are those in which 6, 9, 12, 15, ... motor acts are reproduced. This means that the magnitude of the increment is dependent on a grouping process, which is connected with the specific structure of each problem.

The differences stemming from the different number of blocks in the problems are revealed in the differing learning speeds. Our data show that a sequence containing a smaller number of blocks of greater size (Problem No. 1) is learned at a distinctly greater speed. Evidently, this indicates that grouping into sufficiently large blocks facilitates learning.

Analysis of the distribution of time required to complete a sequence of actions showed that the grouping process is connected not only with learning. Of greatest interest to us are the results of measuring the magnitude of the pauses between consecutive actions. These results indicate that the pauses between two consecutive actions are different, depending on whether these actions are a part of the same block or of two successive blocks. Inter-block pauses are substantially greater than intra-block pauses; in Problem 1 the difference between them was $\geqslant$260 msec, and in Problem No. 2, $\geqslant$230 msec. Obviously, this difference in time is tied in with such characteristics of the problems as the presence of blocks.

One of the possible explanations for the greater length of the inter-block pause is that the time it takes to move the hand over the panel differs because of a certain difference in distance between separate keys. /73

If we return to Fig. 1, where the possible grouping of responses in the problems is shown schematically, it can be observed that the distance the hand has to travel from one key to the next is not the same in all cases. It turns out that hand transfer over the smaller distances is more frequently equivalent to the execution of consecutive actions comprising a single block (the solid arrows) than in transfers from one block to the next.

The second explanation is related to the idea that the structure of the control program is hierarchical, so that the issuance of instructions to execute a block of actions requires a larger number of operations to be completed than instructions to execute individual actions within a block. Such an assumption naturally implies that there is a difference between intra- and inter-block intervals.

We can decide which of these explanations is the real one by measuring the length of the pauses in those segments of the problem in which intra- and inter-block pauses are equivalent to hand transfer over equal distances. Such a segment can be found in Problem No. 1 (Fig. 1). In the transition from block No. 6 to block No. 7, it is necessary to move the hand from key 2 to key 5 (the hand-transfer time in this case is denoted as the inter-block pause); the first intra-block

pause in block No. 7 relates to hand transfer in the opposite direction, from key 5 to key 2, that is, over the same distance. If the first hypothesis is correct, and the difference in magnitude of the inter-and intra-block pauses is actually due to the difference in distances, in the given segment of the sequence there can be no difference in the magnitude of the pauses. But if the second hypothesis is correct, the difference in time should hold.

We made measurements and pairwise comparisons of 190 such intervals for the entire group of test subjects. It turned out that, despite the absence of a difference in distance in moving the hand, the inter-block pause (transfer from key 2 to key 5) exceeds the intra-block pause (transfer from key 5 to key 2) by 258 ± 67.5 msec. This means that the difference in length of the inter- and intra-block pauses is not connected with the hand-transfer time and the distances, but is a characteristic of the control program.

The problem of the nonuniformity in the time of completion of the motor acts themselves (the duration of the key-pressing action) as a function of their position in the block is disputable. It was shown above that in blocks of the four-component sequence, the next to last (third) action proves to be somewhat extended in time, which may be due to the distribution of control commands of the program. It may signify that at this instant preparations begin to execute the next block of actions. The likelihood of such a hypothesis is supported by the fact that in executing the sequence the last block did not reveal a longer third action, as can be seen in Table 6, which shows the averaged data from 86 cases of completion of the block. /74

TABLE 6. Average Duration of Motions in Executing the Last Block of Actions in the Four-Component Sequence (in msec)

Statistical index	Sequential locations of the motions in the block			
	1	2	3	4
$\bar{x}$	460	400	460	460
S	14	10	14	17

But these ideas remain speculative, and this question is in need of further experimental study.

The results obtained in these experiments demonstrate that the time distribution over intervals of completion of a certain motor problem is invariant. This fact makes it possible to set up various test problems with a completely predicted time pattern of execution. This means that such problems are completely suited for evaluation and description of certain aspects of the work of an operator, such as monitoring a sequence of actions. Obviously, the next step in developing such problems as tests is their use under spaceflight simulation conditions.

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